

Controllability of buildings: computing and managing energy in practice

Khalid. Y

Electronic and Electrical Engineering

University of Chester, UK

Email: y.khalid@chester.ac.uk

Abstract

Modern buildings utilise multiple systems for energy generation, supply and storage in order to maintain occupant comfort. Consequently, complex computer based energy management systems are utilised for design and operation of such buildings. Often these buildings perform poor in practice in terms of energy consumption, cost and carbon emissions due to lack of thorough analysis of their controllability during the design process. This paper highlights the deficiencies in the current building design practice and the need for appropriate framework to assess controllability of buildings during design stages so that complex building energy systems are easier to manage in practice.

Keywords: Building Simulation, energy systems, BEMS, controllability, sustainability, design

1. Introduction

Buildings are responsible for about 40% of electricity use in and contribute to approximately 30% of greenhouse gas emissions. Research over the past 20 years has led the design and construction of advanced low-energy buildings, which use novel energy generation and servicing technologies to maintain comfortable internal conditions [1].

Control problems in the buildings industry are not trivial. However, the consequences of failure of plant through bad control are rarely catastrophic. The industry has been able to treat many problems through regular maintenance and commissioning schedules. This has sometimes led to surprisingly good results, but frequently fails to satisfy all the essential occupants and owner's comfort, energy use, operating cost and capital cost requirements [2].

Modern buildings are complex multi-vector energy systems, with physical effects, multiple constraints and control/operational objectives.

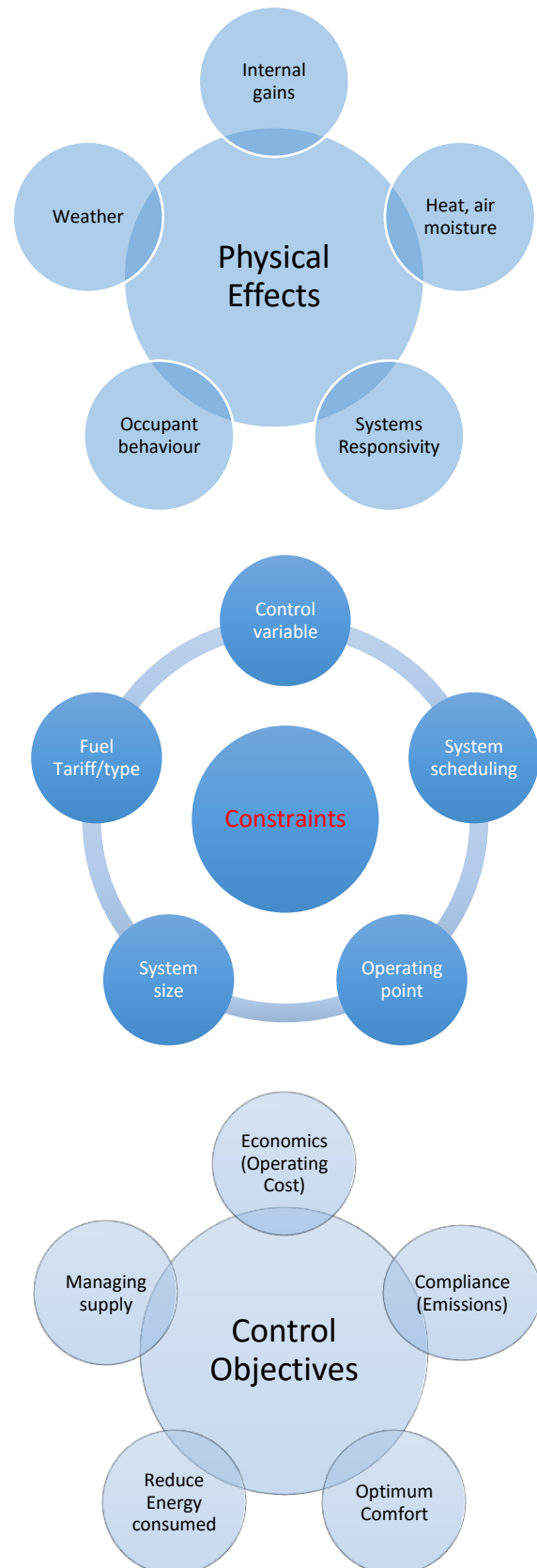


Figure 1 Complex building energy system

This paper discusses the complexity of modern building energy systems and highlights the current practice in designing buildings and the tools used to assess sustainability. It is shown that the process from design to commissioning lacks thorough methodology for assessment of controllability of buildings. The paper discusses the underlying deficiencies in terms of energy simulation, control system design and their application in practice under UK part L building energy regulations. Finally the paper proposes possible ways of integrating controllability methods in the current sustainability assessment framework of building design process.

2. Concept of Controllability

Cars, aeroplanes and buildings are engineering systems that have a lot in common. They all have an envelope, actuator/plant systems, sensors and disturbances. In high technology disciplines such as aerospace systems, engineering science developed decades ago is used at the conceptual design stage to assess the designed system for its controllability [3]. Controllability of a system tells us how easy or difficult it is to control and whether simple controls will do the job or complex controls will be needed.

Computing and managing complex multi-vector energy systems, raises many dynamical and controllability challenges to providing a comfortable internal environment in the face of fluctuating external and internal conditions, energy system dynamics and occupant behaviour.

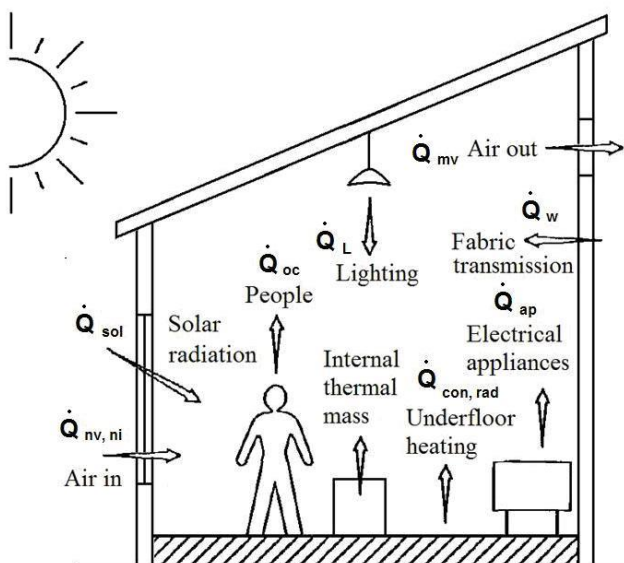


Figure 2 Complex building energy flows [2]

The cross coupled processes occurring between the various parts of the whole building system, leads to complex dynamical behaviour of the building. The cross couplings ultimately lead to systems competing with each other for energy, resulting in uncontrollable system behaviour, poor comfort and high energy consumption and carbon emissions.

Hence an important step in building design process is to assess the strength of these cross couplings between various systems and their minimisation to achieve decoupled systems which are easier to control in practice.

Controllability assessment of the building and its systems at conceptual stage is important because it will solve the current problems of control which arise later in the detailed design phase or at post construction stage where the building services engineer is brought to control the building components.

3. Building Energy Systems

In recent times buildings are utilising many different systems and are composed of highly complex mix of technologies unimaginable few decades ago. These technologies are summarised in as follows:

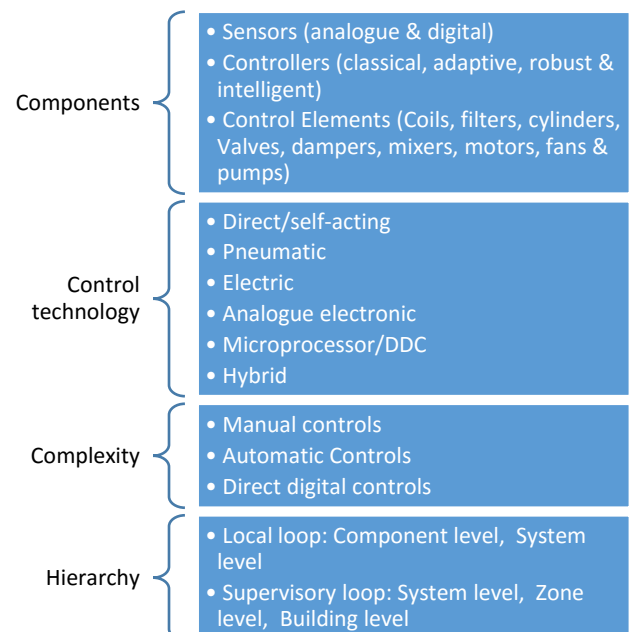


Figure 3 Classification of technologies utilised in modern buildings

These technologies are brought together to create Heating Ventilation and Air Conditioning (HVAC) and lighting systems which manage light, air and hot water for maintaining the comfort conditions.

Current systems utilised in buildings are summarised in the figure below:

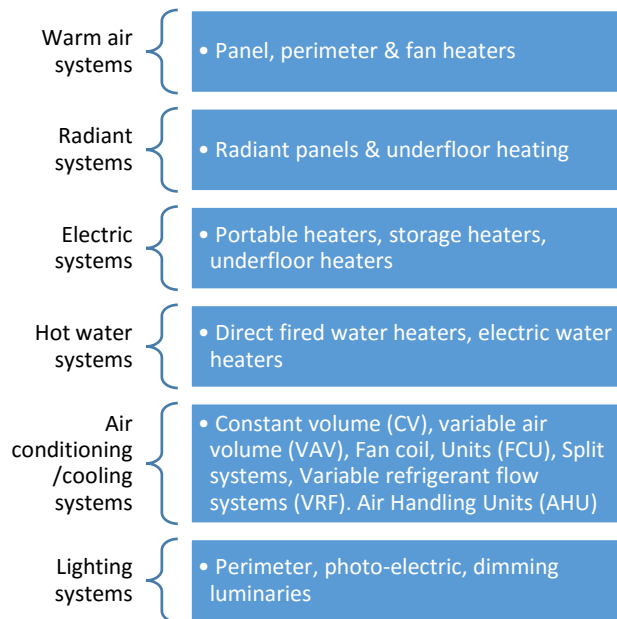


Figure 4 Classification of HVAC systems utilised in modern buildings

The above technologies utilise the power generated, supplied, recovered and stored by the following technologies:

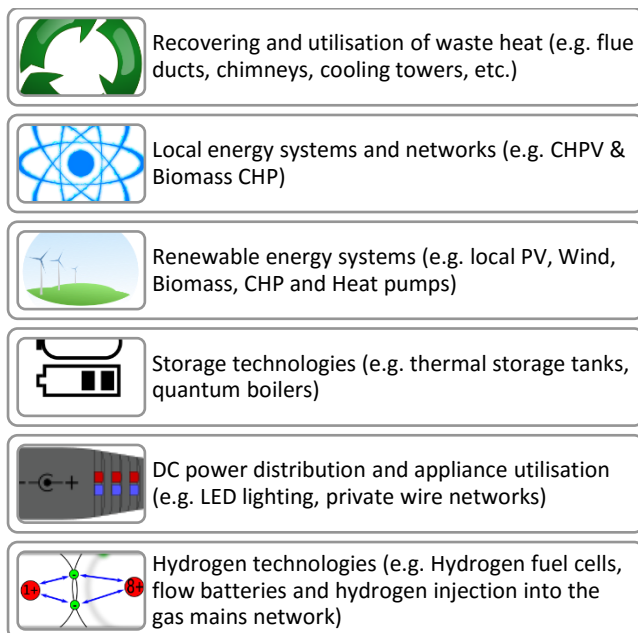


Figure 5 Energy generation and distribution technologies

The above technologies utilise variety of energy sources to produce power: conventional and renewable:



Figure 6 classification of conventional and renewable energy sources [4]

Combination of the above technologies and energy sources when used in a building creates a truly multi-vector energy system.

There is a large range of energy systems available in the market with varying characteristics such as:

- System size
- Location of installation (Wall, roof, floor etc.)
- Energy consumption and efficiency
- System responsiveness (time constant)
- Choice of control variable, sensors and control strategies
- Cost of installation and commissioning
- Energy recovery

The cost of fossil fuels and environmental concerns are increasing and finding novel ways to reduce energy consumption, cost & emissions without compromising comfort and indoor air quality is an ongoing challenge. And as more and more of these technologies are introduced into the building market with the label of energy efficiency, there is a great need for a holistic controllability assessment method in the design process of energy systems.

4. Building Energy Management Systems (BEMS)

In most cases several of these systems are used and operated simultaneously and this has presented control systems designers the challenge to design advanced building energy management systems (BEMS) to successfully control them all simultaneously [1 & 5] BEMS is a high technology control system installed on buildings which performs the overall control and monitoring functions for some or all of the building's plant and systems (mechanical and electrical equipment such as air handling, cooling plant systems, lighting and power systems etc.).

In modern buildings, BEMS is implemented as a networked direct digital control system (shown below) consisting of both software and hardware, display terminals with user interface for system scheduling and control.

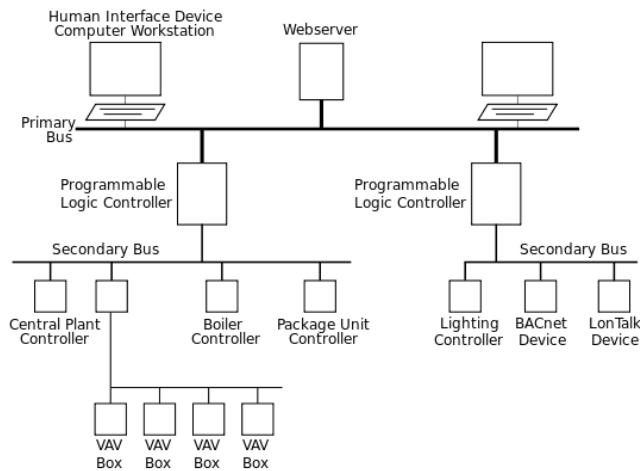


Figure 7 Schematic of BEMS [6]

The whole distributed control system has a hierarchical topology where communication between energy system and controls is carried out through standard building automation communication protocols such as C-Bus and internet enabled protocols such as BACNet and LonWorks [7]. Current control functions/strategies (such as scheduling, resets, lockouts and sequencing/staging) performed by BEMS are summarised in the table below:

Chillers	<ul style="list-style-type: none"> • Entering condenser water temperature reset • Chilled water supply temperature reset • Chilled water secondary loop pressure reset • Chiller staging Chiller system lockout
Cooling tower	<ul style="list-style-type: none"> • Free (or tower) cooling
Boilers	<ul style="list-style-type: none"> • Heating water temperature reset • Heating water secondary loop pressure reset • Boiler system lockout • Boiler sequencing

Table 1 BEMS Control functions and strategies

Many of the BEMS systems and their control functions currently in use do not provide acceptable comfort at all times. And although the energy efficiency of individual pieces of equipment may be improving, the overall efficiency of buildings often falls short of the potential. Poor coordination i.e. unsafe control of equipment operation and the development of faults are common causes of sub-optimal performance and poor comfort [8]. Potential causes for these problems are outlined below:

5. Deficiencies of BEMS in practice

Over the past decade, BEMS have become very highly sophisticated due to advances in digital and wireless communication technologies, sensors and data analytics. The design of BEMS has shifted from using advanced controller design to data mining of building information using advanced sensor and communication technologies. Thus the focus is on understanding and interpreting large sets of building sensor data with thousands of parameters using data analytic algorithms rather than focusing on designing algorithms for control loop based on fundamental physics [9,10,11,12]. This has resulted in a number of issues:

- Hence, BEMS are still using classical control algorithms (e.g. ON/Off and Proportional plus integral plus differential control PID) and thus in terms of controllability, their performance is limited by deficiencies in PID algorithm to deliver decoupled multi-vector control of building energy systems. This is due to PID not

System	Control functions/Strategies
AHU, VAV, FCUs	<ul style="list-style-type: none"> • Dual set point control (dead band) • Zone and system scheduling • Simultaneous heating/cooling control • Night setup/setback • Night cooling • Night purge • Optimum start stop • VAV fan duct pressure and flow reset • Supply/discharge air temperature reset • Hot/cold supply water temperature reset • Mixed air temperature reset • Resistance heat lockout • DX compressor cooling lockout (enthalpy lockout)

effective in dealing with nonlinear behaviour of systems where single input single output loops are implemented without consideration of multivariable nonlinear cross coupled systems physics and thus leading to oscillatory and sluggish system behaviour [13,14,15]

- BEMS technology is too complex for the average user to understand and operate. The result is that many BEMSs are not fulfilling their potential. Rather than scheduling the energy systems they are left on continuously. [14, 16,17]
- Energy-efficient control strategies are not design or included in M&E specifications and generally left to the BEMS professional at commissioning stage rather than designing the control strategy at design stage [18, 19].
- Due to tight time scales of delivery of building at post construction stage and pressure from building control authorities, system engineers are left with commissioning of BEMS for basic operation rather than specific to building design and its systems and physics. This often leads to poor performance of BEMS causing poor post-occupancy satisfaction and high energy usage. [14,20].
- A common problem faced by energy managers is data overload due to mass sensing done by BEMS [10, 11, 12 & 21]. Thus difficult challenges are faced at post occupancy stage of interpreting data into meaning full control strategies and optimisation. Due to large amount of data, data mining algorithms are employed [22] to find meaning full information, however that is often a mathematical exercise rather than providing useful fundamental building physics evaluation and operational strategy [23].

The control strategy behind typical BEMS design and operation is at the root of the problem [22, 23].

Poor design and selection of control strategies is often due to lack of knowledge of the building physics, the dynamics of the whole system including the plant systems and control systems. The result of this is that current control systems (BEMS) are not taking account of the real nature of these buildings; that they are systemic, dynamic and often non-linear. Thus, understanding the dynamic interactions and cross couplings between building and new plant systems along with assessing the feasibility of basic or high performance controls in the light of underlying building physics and control theory has become

even more relevant for building engineers.

Currently the buildings industry lacks the method for controls assessment that is simple, effective and easy to apply across the building design process.

6. The role of Energy Modelling & Simulation Community

The ultimate goal of control systems is to provide flexibility and a high degree of autonomy; effective systems control requires that the underlying system be understood and modelled. On one hand the academic community has utilised modelling and simulation to emulate reality to some degree and to extract conclusions which can be used to improve design. For maximum accuracy, there are integrated simulation package, such as ESP-r, IES-VE, Energy-Plus etc. [24].

These methods attempt to emulate reality, by discretising a system and solving the describing equations numerically. The vast number of nodes required to obtain an accurate picture means that using computer processing is the only practicable way of achieving this. Where possible these tools do not rely on simplifying assumptions. This implies that accurate results will be obtained if the data input is of good quality. As a consequence of this a great deal of information (geometry, materials, climate boundary conditions etc.) must be input before meaningful results can be extracted.

The input and processing required in obtaining accurate results means that this method of modelling can be also time consuming. The modelling and simulation is normally done at the detailed design stage where control strategies are also tested. However, because there is no assessment of controllability in the earlier design stages, there is no guarantee that at the detailed design stage the building and its systems will work in harmony under a particular control strategy offered by the control engineers or selected by the modeller [25]. Although highly detail results are achieved, the detailed simulation of building, systems and controllers makes it difficult to identify the factors affecting controllability. This is due to the large amount of parameters and underlying connections that are not visibly quantified i.e. the cross coupling between modelled systems is not understood [25].

Another drawback of the current simulation tools is that, there are significant differences in how

controls are simulated as opposed to how they are operated in the real world. Real control systems are implemented digitally with error actuated control algorithms operating the control loops. On the other hand in simulation programs, the equations are either inverted or solution is obtained by iterative process in the software code resulting in long simulation times for solution to converge before proceeding with the next simulation time step. Hence real control operation is not mimicked in the simulation. [26, 27]

It is important to note that even the major programs such as IES-VE and Energy-Plus use simplifications such as single node model of air, where air stratification and transport delays are not taken account that are fundamental to controllability assessment. The systems are assumed to be operating with instant response i.e. no delays and thus realistic controls simulation is not fully achieved.

General understanding of how HVAC systems and their control work in reality and how they are modelled and simulation with underlying assumptions are poorly understood by the building simulation professionals. This has led to poor design of controls and their analysis in practice resulting in large performance gaps. [22, 23, 28 & 29]

Hence simulation community still requires a lot of research and development for simulating realistic controls and therefore currently are not making a significant impact on building controls industrial practice. Thus, it is essential to develop methods which bypasses these limitations of simulation programs and which target the fundamental problem of lack of understanding of controllability in the industry by translation of controllability knowledge into a language understood by the different parts of the industry.

7. The role of Building Regulations and Green building guide lines and sustainability practice

As the scientific evidence surrounding climate change has mounted, political will has manifested itself in an outpouring of ‘green’ and ‘sustainable’ policies. Perhaps the most important when considering the built environment are the Building Regulations. The building regulations are at present the only standard that requires compliance used for quantifying the environmental performance of buildings in the U.K. Compliance is measured

based on the energy transfer through the fabric, ventilation and responsivity of the heating systems. Lower overall energy use gives a better energy rating. Currently in the buildings industry, building assessment methods (e.g. BREEAM, LEED) do not assess this property of the building i.e. how easy the building is it to control [25].

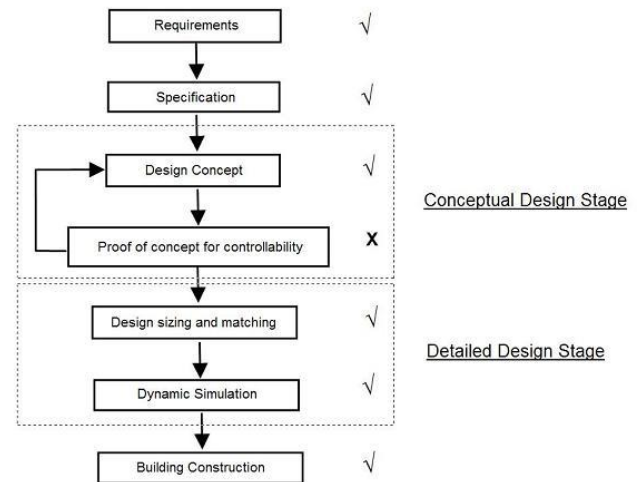


Figure 7 Current building design process (✓ = included x = not included) [25]

Therefore, a low energy rated building in compliance with the building regulations does not guarantee that the building with its systems will be easy to control once built and commissioned.

Hence in many cases BREEAM excellent buildings have performed very poorly in practice [30]. This is because even though the energy assessment is carried out, the designer has not assessed whether the envelope, sensors and plants systems as a whole are compatible with each other to deliver high performance. And this is due to the lack of knowledge of interaction between building physics and building system dynamics.

Commonly used compliance tools in the industry are SAP for dwellings and SBEM for buildings. These tools do not take account of the dynamics of the plant and instead assume Ideal control i.e. the exact plant setting needed based on heat transfers and basic plant information. There is list of control function to select from and corresponding empirical factor is multiplied in the energy calculation [31, 32]. Generally the building and systems are approved based on compliance with the building regulations which take no account of their dynamics and control. This leaves a difficult design task for building services engineer to control an uncontrollable building [25]

Hence, the fundamental problem is that in buildings industry the envelope, sensors and plant systems are assessed for their energy performance individually and collectively in **theory** however fundamentally they are not assessed for their collective operation and performance for **practice**. On the other hand cars and aeroplane designs are thoroughly assessed for this property as failure in these industries results in losses not comparable with buildings.

Thus, understanding the relationship between the properties of building envelope such (i.e. thermal capacities, heat transfer coefficients and densities) and control systems (i.e. controllers and actuators etc.) is very important for designers to design high performance buildings for which they can be confident will comply with building regulations and be robust in performance when faced with design uncertainties.

8. Possible solutions

1. Development and implementation of a holistic controllability rating method for building and their servicing systems

Note: Controllability assessment method is not to test different controllers for the building and investigates which controller is suitable using dynamic simulation. But it is to fundamentally assess the design of the building at the conceptual design stage using fundamental controllability factors to check whether the building is easy or difficult to control without the need for complex controls systems simulation.

The resulting methodology can be part of BREEAM [33] and CFSH [34] assessment methods. It can also be integrated in SBEM for rating the building for controllability along with measures and recommendations to the designer for possible improvements to the design. Hence the architects and designers will not need to perform complex dynamics simulation for testing controls for their building.

Through the BRE Trust funded research this science was successfully applied to buildings energy systems to assess their controllability [35-44]. The controllability of building systems research was a significant step in transferring of the knowledge, understanding and translation of the science to buildings from aerospace discipline.

However further work needs to be done to create best practice guides for different combination of energy systems and building types. This analysis can then form part of the building regulations for the government to implement as a requirement for building design and controllability analysis.

The results of the above research could also be implemented as an independent tool for the industry professional or become part of current simulation tools.

2. Research and development of a new validation criterion for building simulation tools with respect to controllability

The building simulation discipline is constantly evolving, producing a variety of building performance simulation tools. These tools are now more often used in building design worldwide for analysis of sustainability, economic factors, and optimisation, performance and compliance aspects of a building.

There are various bodies which support building simulation discipline that have produced test procedures for their validation. The ASHRAE [45] Standard 140 by ASHRAE and BESTEST by International Energy Agency (IEA) are well-known standards for validation of tools. These standards evaluate the technical capabilities of the tools through the comparison of output results against a set of data, generally absolute outputs from the tools and how they compare between software packages.

However it must be noted that the simulation community does not have a clear criterion to classify and evaluate the facilities offered by tools. More importantly, there is no independent evaluation and classification of tool's capabilities and functionalities in terms of control systems design and performance evaluation.

Thus with the current number of tools numbering in hundreds with inconsistencies in the results, it is not enough that the tools comply with a minimum standard but instead a more thorough method of validation needs to be researched and created. A method which judges the simulation tools based on their ability to predict realistic performance of energy systems and their controllability based on a specific set of building cases rather than idealised performance above a certain notional building

model.

With building energy modelling becoming an essential part of Government environmental policies and certification systems, it is critical that alternative software packages are tested and validated to produce accurate and consistent predictions in their analysis.

Current validation systems are very restrictive and limited. The new methodology for validation would benefit the software vendors community by providing a validation system that provides detailed feedback on which areas of their system are affecting their ability to predict results accurately; the modelling community through the improved set of tools that would be produced through this validation system; and the systems and policies dependent on such building energy modelling tools (i.e. BREEAM in Use, certification schemes, government policies, etc.).

9. Conclusion

As the complexity of modern built environment has increased, the efficient control, economic and safe operation of mechanical services has become a more complex issue. There is a need to adopt a holistic approach to controllability assessment in the design process which integrates the architects, building services engineers, control engineers, modelling and simulation community.

It is also agreed upon that there is general lack of understanding of control systems engineering and an engineering science which can give insight into controllability that the building industry can understand and use effectively will lead to better design of buildings by addressing problems at their root and not just treating their symptoms. What is needed is a complete methodology for assessing buildings for their controllability and a framework for rating them in practice.

This will allow designer to design easy to control buildings using simple controls, with the need for advanced controls and without the need to know complex aerospace systems engineering controllability design science and dynamic simulation. At the same time controllability needs to be inbuilt in simulation tools for feasibility analysis and virtual trials of energy systems solutions taking account their dynamics and limitations.

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